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Is the ee$\gamma\gamma + \not{E}_T$ Event an Evidence of the Light Axino?

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Abstract

We point out that if the Peccei-Quinn symmetry breaking scale F_a is in a range of the hadronic axion window ($F_a \sim 10^6$GeV), the ee$\gamma\gamma + \not{E}_T$ event in the CDF experiment can be naturally explained by a no-scale supergravity model with a light axino. We also stress that the hadronic axion window still survives the intergalactic photon search, since a large entropy production due to the decay of Polonyi field yields a substantial dilution of the cosmic axion density.

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The no-scale supergravity [1] has attracted many physicists in particle physics, since it may arise from a class of space-time compactifications in superstring theories [2]. It is also interesting in cosmology, since it can naturally accommodate the chaotic inflation [3], but it also provides a consistent solution [4] to the serious cosmological problem in supergravity; *i.e.*, the Polonyi problem [5]. However, it has been recently pointed out [6] that one needs a new fine tuning to solve the Polonyi problem if the usual lightest supersymmetric particle (LSP) (which is perhaps a bino-dominated neutralino) is stable [4]. Therefore, we are led to consider the unstable "LSP". A possible way to have the unstable "LSP" is to break R parity. In this case, however, we must invoke the other mechanism to avoid a rapid proton decay. In Ref. [6] it has been suggested that the bino-dominated "LSP" (we call it, "bino", hereafter) decays into the axino (a fermionic superpartner of the axion) [7], since there is a possibility that the axino remains light even after supersymmetry (SUSY) breaking and becomes the true LSP in the no-scale supergravity model [8].

In this letter we point out that if the Peccei-Quinn (PQ) symmetry breaking scale F_a lies in a range of the hadronic axion window ($F_a/N = (0.7-2)\times 10^6$GeV with N being the QCD anomaly factor of the PQ symmetry) [9], the "bino" decay into the axino can explain the ee$\gamma\gamma+\not{E}_T$ event recently observed in the CDF experiment [10]. We also stress that the constraint on the hadronic axion window derived from the intergalactic photon search [11][9] is irrelevant in our no-scale supergravity model, since the decay of the Polonyi field produces a large amount of entropy at the late epoch of the universe evolution and dilutes the abundance of the cosmic axion density substantially. (The dilution factor for relativistic particles is about 10^{-13}.)[‡]

We consider, in this letter, an example of SUSY hadronic axion model [12]. The extension of our analysis based on more general models is straightforward. We assume N pairs of massless new chiral superfields $\Psi_A = (Q, L)_A$ and $\bar{\Psi}_A = (\bar{Q}, \bar{L})_A$ ($A = 1-N$) which transform as **5** and **5*** under the grand unified gauge group SU(5)$_{\rm GUT}$, respectively, in addition to the SUSY standard model (SM) sector. They are assumed to have the PQ charge +1 and hence there are massless as far as the

[‡] In Ref. [4] it is shown that enough baryon asymmetry is created in spite of the large entropy production if we assume the Affleck-Dine mechanism for baryogenesis.

PQ symmetry is unbroken. All fields in the SUSY SM sector have no PQ charge. In order to break the PQ symmetry we introduce a superfield Φ whose PQ charge is set as -2 so that the Φ can couple to the N pairs of Ψ and $\bar{\Psi}$ as

$$W = \lambda_A \bar{\Psi}_A \Psi_A \Phi. \tag{1}$$

We assume that some physics involving the Φ field gives a nonzero vacuum expectation value to the Φ and then the PQ symmetry is spontaneously broken by the vacuum condensation $\langle \Phi \rangle \neq 0$.

The Nambu-Goldstone chiral multiplet arising from the PQ symmetry breaking contains pseudo-scalar field axion $a(x)$, real-scalar field saxion $s(x)$, and their fermionic partner called axino $\tilde{a}(x)$. The N pairs of $\bar{\Psi}$ and Ψ have masses of $\lambda_A \langle \Phi \rangle$. The axion acquires a mass of order of $\Lambda_{\rm QCD}^2 / \langle \Phi \rangle$ through QCD instanton effects, where $\Lambda_{\rm QCD}$ is the QCD scale $\sim$ 100MeV. On the other hand, the axino gets a mass[§]

$$m_{\tilde{a}} \simeq \sum_A \frac{1}{16\pi^2} \lambda_A^2 m_{\rm SUSY} \tag{2}$$

through one loop diagrams in the no-scale supergravity model as shown in Ref. [14]. Here, the $m_{\rm SUSY}$ is an induced SUSY breaking soft mass of Ψ and $\bar{\Psi}$. If one takes $m_{\rm SUSY} \sim O(100)$GeV and $\lambda_A \sim O(0.1)$, one gets $m_{\tilde{a}} \sim O(10)$MeV. Notice that this axino $\tilde{a}$ is harmless in cosmology since the large entropy production from the Polonyi field decay dilutes the axino density substantially. This large entropy production is also very important to dilute the cosmic axion density as stressed in the introduction.

A crucial point in this letter is that the axion superfield $\Phi_a(x, \theta)$ couples to the gauge superfields through anomalies of the PQ current as

$$\mathcal{L} = -\sqrt{2} \frac{\alpha_i}{8\pi} \int d^2\theta \frac{\Phi_a}{F_a/N} W_\alpha^i W_\alpha^i, \tag{3}$$

where $F_a = \langle \Phi \rangle$, and W_α^i $(i = 1-3)$ are gauge superfields of the SM gauge groups $\mathrm{U}(1)_Y$, $\mathrm{SU}(2)_L$, and $\mathrm{SU}(3)_C$, and α_i are corresponding gauge coupling constants

[§] The saxion mass is given by $m_s^2 = \sum_A (c/16\pi^2) \lambda_A^2 m_{SUSY}^2$ with $c \sim O(1)$. If one takes $m_{\rm SUSY} \sim O(100)$GeV and $\lambda_A \sim O(0.1)$, one gets $m_s \sim O(1)$GeV. This is cosmologically harmless since the lifetime $\tau_{s \to gg}$ is 10^{-7} sec. for $F_a = 10^6$GeV [13].

($\alpha_1 = 5/3\alpha_Y = 0.017$, $\alpha_2 = 0.034$, and $\alpha_3 = 0.12$ at the electroweak scale). This induced interactions in Eq. (3) contain a bino-axino-photon coupling as

$$\mathcal{L} = -\frac{5\alpha_{em}}{24\pi}\frac{1}{\cos\theta_W}\frac{1}{F_a/N}\bar{\tilde{a}}\gamma_5\sigma_{\mu\nu}\tilde{B}F^{\mu\nu}, \tag{4}$$

from which we can estimate the decay width of $\tilde{B} \to \tilde{a} + \gamma$ as

$$\Gamma(\tilde{B} \to \tilde{a} + \gamma) = \frac{25\alpha_{em}^2}{1152\pi^3}\frac{1}{\cos^2\theta_W}\frac{M_{\tilde{B}}^3}{(F_a/N)^2} \tag{5}$$

where $M_{\tilde{B}}$ is the bino mass, and then,¶

$$c\tau_{\tilde{B}} = 0.36\ \left(\frac{100\text{GeV}}{M_{\tilde{B}}}\right)^3 \left(\frac{F_a/N}{10^6\text{GeV}}\right)^2\ \text{c.m..} \tag{6}$$

We are now at the point of this letter. If the F_a lies in the range of hadronic axion window [9], *i.e.*,

$$F_a/N \simeq (0.7 - 2) \times 10^6\ \ \text{GeV}, \tag{7}$$

we obtain

$$c\tau_{\tilde{B}} = (0.18 - 1.44)\ \text{c.m.}, \tag{8}$$

for $M_{\tilde{B}} = 100$GeV. It is now clear that the $\tilde{B} \to \tilde{a} + \gamma$ decay can be a source of the hard photon in the ee$\gamma\gamma + \not{E}_T$ event observed in the CDF experiment [10].

It has been already shown in recent papers [15] that masses of a selectron $\tilde{e}$ and the "bino" $\tilde{B}$ must be $m_{\tilde{e}} = (80 - 130)$GeV, and $M_{\tilde{B}} = (38 - 100)$GeV to explain the ee$\gamma\gamma + \not{E}_T$ event by sequent decays; $\tilde{e}^-(\tilde{e}^+) \to e^-(e^+) + \tilde{B}$ and $\tilde{B} \to \gamma + \text{LSP}$. Let us now discuss the low-energy mass spectrum of SUSY particles in our model, and show that it is very much welcome to this event. In the no-scale supergravity model sfermion masses are induced by the SM gauge interactions with non-vanishing gaugino masses. Then, the right-handed selectron and the "bino" are naturally expected to be the lightest two among SUSY particles except for the axino, since they have only the U$(1)_Y$ gauge interaction. (See Ref. [16] for a detailed calculation.) We use renormalization group (RG) equations to evaluate a ratio of the right-handed

¶ The decay $\tilde{B} \to \tilde{a}+\gamma$ is the main decay mode. Thus, the branching ratio Br$(\tilde{B} \to \tilde{a}+\gamma) \simeq 100\%$ which is also a favorable point for explaining the ee$\gamma\gamma + \not{E}_T$ event.

selectron to the bino masses. The RG equations of the right-handed selectron mass ($m_{\tilde{e}_R}$) and the bino mass ($M_{\tilde{B}}$) above the mass scale of Ψ and $\bar{\Psi}$ are

$$\begin{aligned} \mu\frac{\partial m^2_{\tilde{e}_R}}{\partial\mu} &= -8\frac{\alpha_Y}{4\pi}M^2_{\tilde{B}}, \\ \mu\frac{\partial M_{\tilde{B}}}{\partial\mu} &= 2b_Y\frac{\alpha_Y}{4\pi}M_{\tilde{B}}, \end{aligned} \tag{9}$$

where $b_Y(=11+5N/3)$ is a coefficient of beta function of the $\mathrm{U}(1)_Y$ gauge coupling constant and μ the renormalization point. These equations become those of the SUSY SM below the mass scale of Ψ and $\bar{\Psi}$. If the no-scale boundary conditions for these masses such as $m_{\tilde{e}_R}=0$ is imposed at $\mu=10^{16}$GeV, the mass ratio between the right-handed selectron and the "bino" at the electroweak scale is given by

$$\frac{m_{\tilde{e}_R}}{M_{\tilde{B}}} = \begin{cases} 1.1 & (N=1) \\ 1.3 & (N=2) \\ 1.7 & (N=3) \\ 2.6 & (N=4) \end{cases} . \tag{10}$$

Here, the masses of Ψ and $\bar{\Psi}$ are taken at 10^5GeV. The mass ratios for $N=2,3$ are suitable to the ee$\gamma\gamma+\not{E}_T$ event in the CDF experiment as shown in Refs. [15][17][18]. The masses of $m_{\tilde{e}_R}$ and $M_{\tilde{B}}$ themselves take the values around 100 GeV to cause the correct electroweak symmetry breaking as shown in Ref. [16], which are also desirable for the explanation of the event. Notice that the right-handed selectron is heavier than wino ($\tilde{W}$) for $N=4$ if the gaugino masses satisfy the GUT relation ($M_{\tilde{W}}\simeq 2M_{\tilde{B}}$). In this case, the CDF event can have another interpretation that it is a wino pair production accompanied with the sequent decays as $\tilde{W}^-(\tilde{W}^+)\to e^-(e^+)+\bar{\nu}(\nu)+\tilde{B}$ and $\tilde{W}^0\to e^-(\nu)+e^+(\bar{\nu})+\tilde{B}$, assuming two body decays into $W^\pm(Z^0)+\tilde{B}$ are suppressed by phase space (that is, $M_{\tilde{W}}-M_{\tilde{B}}<m_W(m_Z)$) [17][19]. If this interpretation is right, it is expected to observe multi-leptons and 2 photons events with missing energy.[‖] If the boundary condition is given at the gravitational scale ($\mu=10^{18}$GeV), the mass ratio of the right-handed selectron to the "bino" becomes larger, and we can get the suitable mass spectrum even for $N=1$ case ($m_{\tilde{e}_R}/M_{\tilde{B}}=1.6$).

‖ The decay into jets is suppressed since squarks are heavier than sleptons due to the $\mathrm{SU}(3)_C$ interactions.

So far we do not have taken constraints from the effects of axion emission upon the life cycle of red-giant (RG) and horizontal-branch (HB) stars in our analysis, since these constraints are based on the statistics of small number [9]. If one takes the constraints seriously, one obtains [20]

$$F_a/N > 3 \times 10^6 \text{ GeV} \qquad \text{(RG)}, \tag{11}$$
$$F_a/N > 9 \times 10^6 \text{ GeV} \qquad \text{(HB)}, \tag{12}$$

which is already outside the axion window. However, this problem can be easily solved, since the axion-photon-photon ($a\gamma\gamma$) coupling depends on the details of models [21]. For example, we assign the different PQ charges Q_L and Q_Q to the doublet L and triplet Q, respectively. ** Then, we obtain the $a\gamma\gamma$ coupling as

$$\mathcal{L}_{a\gamma\gamma} = \frac{\kappa}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}, \tag{13}$$
$$\kappa = \frac{\alpha_{em}}{2\pi}\frac{1}{F_a/N}\left[\frac{2}{3}(1+3\gamma) - \frac{2(4+z)}{3(1+z)}\right], \tag{14}$$

where γ is the ratio of the PQ charge, $\gamma = Q_L/Q_Q$ and z the mass ratio of up- and down-quarks, $z = m_u/m_d$. Notice that the second term in the bracket of Eq.(14) denotes the contribution from the long-distance effect. We can see that $a\gamma\gamma$ coupling is almost vanishing for $z \simeq 0.56$ and $\gamma \simeq 2/3$. In this case, the above constraints from RG and HB stars become weaker [9]

$$F_a/N > 0.2 \times 10^6 \text{ GeV} \qquad \text{(RG)}, \tag{15}$$
$$F_a/N > 0.6 \times 10^6 \text{ GeV} \qquad \text{(HB)}, \tag{16}$$

since subject to the constraints is the $a\gamma\gamma$ coupling strength but not F_a itself. On the other hand, the bino-axino-photon ($\tilde{B}\tilde{a}\gamma$) coupling does not have the contribution from the long-distance effect and hence there is not such a cancellation in the $\tilde{B}\tilde{a}\gamma$ coupling. Thus, the analysis in this paper is unchanged.

In summary, we argue that the hadronic axion window is not yet excluded by the intergalactic photon search, since there is a substantial dilution of the cosmic axion

**Since L and Q have different PQ charges, the multiplets $\Psi_A(Q,L)$ and $\bar{\Psi}_A(\bar{Q},\bar{L})$ do not form $\mathrm{SU}(5)_{\mathrm{GUT}}$ multiplets.

density in the no-scale supergravity model. If the PQ symmetry breaking scale is in the hadronic axion window, the ee$\gamma\gamma + \not{E}_T$ event in the CDF experiment can be naturally interpreted as a result of the cascade decays; $\tilde{e}_R^-(\tilde{e}_R^+) \rightarrow e^-(e^+) + \tilde{B}$ and $\tilde{B} \rightarrow \text{axino} + \gamma$. We hope that this hadronic axion window will be tested by future axion searches [22].

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